Charm physics: theoretical review

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We review recent developments in charm physics, focusing on the physics of charmed mesons. We discuss charm spectroscopy, decay constants, as well as searches for new physics with charmed mesons. We discuss $D^0 - \overline{D}^0$ mixing and CP-violation in charm decays. We also present the modified Nelson plot of charm mixing predictions.

1   Introduction

Charm physics plays a unique dual role in the modern investigations of flavor physics. Charm decay and production experiments provide valuable checks and supporting measurements for studies of CP-violation in measurements of CKM parameters in b-physics, as well as outstanding opportunities for searches for new physics. Historically, many methods of heavy quark physics have been first tested in charmed hadrons. The fact that a b-quark mainly decays into a charm quark makes charm physics an integral part of any b-physics program. In many cases, direct measurements of charm decay parameters directly affect the studies of fundamental electroweak physics in B decays [1].

This year brought several interesting developments in some seemingly well-understood sectors of charm physics, such as meson spectroscopy. Here I shall discuss theoretical implications of these and other results. The experimental status of charmed meson spectroscopy was discussed in R. Chistov's talk [2]. Resent results in the measurements of charmed meson formfactors, lifetimes and $D^0 - \overline{D}^0$ mixing parameters were discussed by W. Johns [3] and G. Boca [4].

2   Spectroscopy

Meson spectroscopy is an important laboratory for understanding quark confinement. Mesons containing one heavy quark can provide valuable information about the structure of the QCD Lagrangian, as spectroscopic considerations simplify significantly in the limit of infinitely heavy quark, $m_Q/\Lambda \to \infty$, where Λ represents a typical scale of hadronic interactions. While charm quark hardly satisfies this conditions, it is nethertheless useful to apply these considerations to the charmed quark systems. In this limit the heavy quark spin S_Q decouples, so the total angular momentum of the light degrees of freedom J_l^p becomes a "good" quantum number. Since parity of a meson can be obtained by knowing the angular momentum quantum number l as $(-1)^{l+1}$, this leads to an important prediction of heavy quark symmetry: the appearance

of heavy meson states in the form of degenerate parity doublets classified by the total angular momentum of the light degrees of freedom (see Table (1)),

$$S^p = J_l^p \pm \frac{1}{2}. \tag{1}$$

This mass degeneracy is lifted with the inclusion of subleading $1/m_Q$ corrections. This useful picture is built into many quark-model descriptions of heavy meson spectra. The resulting models have been very successful in explaining the spectrum of negative-parity scalar and vector $J_l^p = 1/2^-$ and positive-parity vector and tensor $J_l^p = 3/2^+$ states. A narrow resonance

L	0	1		2	
J_l	$1/2$	$1/2$	$3/2$	$3/2$	$5/2$
S	$0, 1$	$0, 1$	$1, 2$	$1, 2$	$2, 3$

Table 1: Total angular momentum assignments for heavy-light mesons

in $D_s^+ \pi^0$ was recently reported by BaBar [5] and confirmed by the CLEO [6] and Belle [7] collaborations. Its decay patterns suggest a quark-model 0^+ classification, which would identify it with the positive-parity $J_l^p = 1/2^+$ p-wave state. As in the D meson system, p-wave states for the D_s^+ system are expected, and two narrow states, $D_{s1}(2536)$ and $D_{s2}(2573)$ were discovered by ARGUS and CLEO, respectively [8]. In analogy to the D system, two broad states are also expected.

The mass of the new state 2317.6 ± 1.3 MeV appears surprisingly low and its width appears to be too small for quark model practitioners. In fact, this state appears below DK threshold, closing off the most natural decay channel for this state. This forces it to decay mainly via an isospin-violating transition into the $D_s^+ \pi^0$ final state which makes its width quite narrow. Its mass disagrees with most predictions of quark models [9, 10, 11, 12, 13, 14] available prior to its observation. For example, a mass of 2487 MeV is obtained in the potential model calculation by Eichten and Di Pierro [10]. Quenched lattice calculations also seem to favor larger values of the mass of this state [15] (see, however, [16]). This led to a lively discussion of the possible

Reference	0^+ mass	1^+ mass
Ebert et al (98) [14]	2.51 GeV	2.57 GeV
Godfrey-Isgur (85) [9]	2.48 GeV	2.55 GeV
DiPierro-Eichten (01) [10]	2.49 GeV	2.54 GeV
Gupta-Johnson (95) [11]	2.38 GeV	2.52 GeV
Zeng et al (95) [12]	2.38 GeV	2.51 GeV
Experiment	2.317 GeV	2.463 GeV

Table 2: Theoretical predictions for masses of 0^+ and 1^+ D_s states

non-$q\bar{q}$ nature of this state [18, 19, 20, 21]. A possibility of a state that is an admixture of a four-quark state and a $q\bar{q}$ states was discussed in [27]. In addition, a second narrow state is

observed in $D_s^{*+}\pi^0$ at a mass near 2460 MeV [6, 7]. This state would naturally be identified as a spin 1 positive parity p-wave meson. However, its mass also appears too low for the potential model expectations (e.g. 2605 MeV [10, 28], see also Table 2). Its radiative decays to the ground state D_s meson were observed with

$$\frac{\Gamma(D_{sJ}(2460) \to D_s\gamma)}{\Gamma(D_{sJ}(2460) \to D_s\pi^0)} = 0.44 \pm 0.10, \tag{2}$$

while doubly charged states were not observed in $D_s^\pm\pi^\pm$ channels. Finally, D_{sJ} states were also observed in B-decays $B \to DD_{sJ}^{(*)}$.

The low values of the masses for these states, however, do not signal a breakdown of quark-model descriptions of the heavy meson spectrum, as it is difficult to assess the accuracy of these predictions, especially in the charm sector. Many authors make use of the non-relativistic nature of the charm quark, taking into account $1/m_c$ corrections only. For the 0^+ state, quark model predictions range from the values of $2387 - 2395$ MeV [11, 13] (still above the DK threshold) on the low end of the spectrum to 2508 MeV [14] on the high end. Since the described phenomena are highly non-perturbative, one should be careful before making a judgment on the nature of a given state based solely on the prediction of a given quark model. For example, as discussed above, in the $m_c \to \infty$ limit the 0^+ and 1^+ states are expected to become degenerate in mass, $m_{0^+}, m_{1^+} \to M$. This can be emulated in quark models by neglecting heavy-quark symmetry-violating $1/m_c$ corrections. Yet, different quark models predict very different behavior in this "heavy-quark limit": for instance, one potential model [11] predicts that the mass M of the $(0^+, 1^+)$ multiplet will decrease to approximately 2382 MeV (which is less than the mass of the 0^+ state predicted in this model with the full potential), while in a QCD string model [13] it is expected to increase up to 2500 MeV (which is much greater than the mass of the 0^+ state predicted in this model with the full potential). In addition, quark models, modified to include chiral symmetry constraints, generally predicted lower values of mass splitting between $(0^-, 1^-)$ and $(0^+, 1^+)$ multiplets, of the order of $200 - 300$ MeV [17]. In addition, one has to remember that most of the unusial details about these states, such as narrowness of their decay widths, simply follows from the fact that the mass of that state is smaller than the $D^{(*)}K$ threshold. It is then only the fact that the new state appears below DK threshold and is almost degenerate with a non-strange 0^+ p-wave D state [22] is curious and deserves an investigation, although could be purely accidental.

A combination of experimental measurements described above can shed some light onto the nature of these states. For instance, molecular-type explanation of the low masses of these states implies the existence of the doubly-charged states, which were not observed. On the contrary, a possible disagreement of the observed branching ratios of B decays into these states with calculations of their branching ratios in naive factorization could favor molecular nature of these states [29]. But it could as well signal a breakdown of naive factorization in B decays into the pair of $0^-, 0^+(1^+)$ open-charm states, which was never really tested, or simply reflect our ignorance of the decay constants of positive parity mesons [30]. The observation of the radiative decay of $D_{sJ}(2460)$ favors $q\bar{q}$ (or maybe $q\bar{q}$-four-quark-state admixture) explanation of the nature of these mesons.

3 Decay constants and B-physics experiments.

Since m_b, $m_c \gg \Lambda_{QCD}$, both charm and bottom quarks can be regarded as heavy quarks [1]. Naturally, heavy quark symmetry relates observables in B and D transitions. As an example, let us consider measurements in the charm sector affect determinations of the CKM matrix elements relevant to top quark in $B^0 - \overline{B}^0$ mixing.

A mass difference of mass eigenstates in $B^0 - \overline{B}^0$ system can be written as

$$\Delta m_d = C \left[\alpha_s^{(5)}(\mu)\right]^{-6/23} \left[1 + \frac{\alpha_s^{(5)}(\mu)}{4\pi} J_5\right] \langle \overline{B}_d^0 | O(\mu) | B_d^0 \rangle, \tag{3}$$

where $C = G_F^2 M_W^2 \left(V_{tb}^* V_{td}\right)^2 \eta_B m_B S_0(x_t) / \left(4\pi^2\right)$ (see Ref. [31] for complete definitions of the parameters in this expression). The largest uncertainty of about 30% in the theoretical calculation is introduced by the poorly known hadronic matrix element $A = \langle \overline{B}^0 | O(\mu) | B^0 \rangle$. Evaluation of this matrix element is a genuine non-perturbative task, which can be approached with several different techniques. The simplest approach ("factorization") reduces the matrix element A to the product of matrix elements measured in leptonic B decays $A^f = (8/3) \langle \overline{B}^0 | \overline{b}_L \gamma_\sigma d_L | 0 \rangle \langle 0 | \overline{b}_L \gamma^\sigma d_L | B^0 \rangle = (2/3) f_B^2 m_B^2$, where we employed the definition of the decay constant f_B,

$$\langle 0 | \overline{b}_L \gamma_\mu d_L | B^0(\mathbf{p}) \rangle = i p_\mu f_B / 2. \tag{4}$$

A deviation from the factorization ansatz is usually described by the parameter B_{B_d} defined as $A = B_{B_d} A^f$; in factorization $B_{B_d} = 1$. Similar considerations lead to an introduction of the parameter B_{B_s} defined for mixing of B_s mesons. It is important to note that the parameters B_{B_q} depend on the chosen renormalization scale and scheme. It is convenient to introduce renormalization-group invariant parameters $\hat{B}_{B_q}$

$$\hat{B}_{B_q} = \left[\alpha_s^{(5)}(\mu)\right]^{-6/23} \left[1 + \frac{\alpha_s^{(5)}(\mu)}{4\pi} J_5\right] B_{B_q}. \tag{5}$$

We provide averages of $\hat{B}_{B_q}$, as well as the ratio $\hat{B}_{B_s}/\hat{B}_{B_d}$ from the review [32] as well as from two more recent evaluations [33, 34] in Table 3. Thus, at least naively, one can determine CKM matrix element V_{td} by measuring f_B and Δm_d and computing B_{B_q}.

This direct approach, however, meets several difficulties. First, leptonic decay constant f_B can in principle be extracted from leptonic decays of charged B mesons. The corresponding decay width is

$$\Gamma(B \to l\nu) = \frac{G_F^2}{8\pi} f_B^2 |V_{ub}|^2 m_l^2 m_B \left(1 - \frac{m_l^2}{m_B^2}\right). \tag{6}$$

This width is seen to be quite small due to the smallness of the CKM factor $|V_{ub}|$ and helicity suppression factor of m_l^2. In addition, experimental difficulties are also expected due to the backgrounds stemming from the presence of a neutrino in the final state.

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[1]This approximation obviously works better for bottom than for charm quarks.

Method (reference)	$\hat{B}_{B_d}$	$\hat{B}_{B_s}/\hat{B}_{B_d}$
Lattice, '03 [32]	1.34(12)	1.00(3)
QCDSR, '03 [32]	1.67 ± 0.23	≈ 1
Lattice, '03 [33]	$1.277(88)\binom{+86}{-95}$	$1.017(16)\binom{+56}{-17}$
QCDSR, '03 [34]	1.60 ± 0.03	≈ 1

Table 3: Renormalization-group independent B-parameters.

Second, computation of B_{B_q} is quite difficult and requires the use of non-perturbative techniques such as lattice or QCD Sum Rules. Current uncertainties in the determinations of f_B and B_{B_q} are quite large. It turns out that evaluation of the ratio of

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \left[\frac{\sqrt{B_{B_d}} f_{B_d}}{\sqrt{B_{B_s}} f_{B_s}} \right]^2 \left| \frac{V_{td}}{V_{ts}} \right|^2, \tag{7}$$

is favored by lattice community, as many systematic errors cancel in this ratio. This gives a ratio of $|V_{td}/V_{ts}|$, which provides a non-trivial constraint on CKM parameters in the $\rho-\eta$ plane.

Instead, one can make use of ample statistics available in charm production experiments, as heavy quark and $SU(3)$ flavor symmetries relate the ratio of charm decay constants f_{D_s}/f_D to beauty decay constants f_{B_s}/f_B

$$\frac{f_{B_s}/f_B}{f_{D_s}/f_D} = 1 + O(m_s) \times O(1/m_b - 1/m_c). \tag{8}$$

Note that SU(3)-violating corrections can also be evaluated in chiral perturbation theory [35]. One still needs to rely on the theoretical determination of B_{B_q}.

Similar techniques of relating B and D decays can also be used to extract other CKM matrix elements, like V_{ub} [36], studies of lifetime patterns of heavy hadrons [37], and tuning lattice QCD calculations [38].

4 Charm mixing and CP violation

One of the important areas of modern phenomenology where charm decays play an important role is the indirect search for physics beyond the Standard Model. Indeed, large statistics usually available in charm physics experiment makes it possible to probe small effects that might be generated by the presence of new physics particles and interactions. A program of searches for new physics in charm is complimentary to the corresponding programs in bottom or strange systems. This is in part due to the fact loop-dominated processes such as $D^0 - \overline{D}^0$ mixing or flavor-changing neutral current (FCNC) decays are sensitive to the dynamics of ultra-heavy *down-type particles*. Also, in many dynamical models, including the Standard Model, the effects in s, c, and b systems are correlated.

The low energy effect of new physics particles can be naturally written in terms of a series of local operators of increasing dimension generating $\Delta C = 1$ (decays) or $\Delta C = 2$ (mixing)

transitions. For $D^0 - \overline{D}^0$ mixing these operators, as well as the one loop Standard Model effects, generate contributions to the effective operators that change D^0 state into $\overline{D}^0$ state leading to the mass eigenstates

$$|D_{\frac{1}{2}}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \qquad (9)$$

where the complex parameters p and q are obtained from diagonalizing the $D^0 - \overline{D}^0$ mass matrix. The mass and width splittings between these eigenstates are given by

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}. \qquad (10)$$

It is known experimentally that $D^0 - \overline{D}^0$ mixing proceeds extremely slowly, which in the Standard Model is usually attributed to the absence of superheavy quarks destroying GIM cancellations [39].

It is instructive to see how new physics can affect charm mixing. Since the lifetime difference y is constructed from the decays of D into physical states, it should be dominated by the Standard Model contributions, unless new physics significantly modifies $\Delta C = 1$ interactions. On the contrary, the mass difference x can receive contributions from all energy scales. Thus, it is usually conjectured that new physics can significantly modify x leading to the inequality $x \gg y$ [2]. The same considerations apply to FCNC decays as well, where new physics could possibly contribute to the decay rates of $D \to X_u \gamma$, $D \to X_u l^+ l^-$ (with X_u being exclusive or inclusive final state) as well as other observables [42]. One technical problem here is that in the standard model these decays are overwhelmingly dominated by long-distance effects, which makes them extremely difficult to predict model-independently. This problem can be turned into a virtue [43].

Another possible manifestation of new physics interactions in the charm system is associated with the observation of (large) CP-violation. This is due to the fact that all quarks that build up the hadronic states in weak decays of charm mesons belong to the first two generations. Since 2×2 Cabbibo quark mixing matrix is real, no CP-violation is possible in the dominant tree-level diagrams that describe the decay amplitudes. In the Standard Model CP-violating amplitudes can be introduced by including penguin or box operators induced by virtual b-quarks. However, their contributions are strongly suppressed by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$. It is thus widely believed that the observation of (large) CP violation in charm decays or mixing would be an unambiguous sign for new physics. This fact makes charm decays a valuable tool in searching for new physics, since the statistics available in charm physics experiment is usually quite large.

As in B-physics, CP-violating contributions in charm can be generally classified by three different categories: (I) CP violation in the decay amplitudes. This type of CP violation occurs when the absolute value of the decay amplitude for D to decay to a final state f (A_f) is different from the one of corresponding CP-conjugated amplitude ("direct CP-violation"); (II) CP violation in $D^0 - \overline{D}^0$ mixing matrix. This type of CP violation is manifest when $R_m^2 = |p/q|^2 = (2M_{12} - i\Gamma_{12})/(2M_{12}^* - i\Gamma_{12}^*) \neq 1$; and (III) CP violation in the interference of decays with and without mixing. This type of CP violation is possible for a subset of final states to which both D^0 and $\overline{D}^0$ can decay.

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[2]This signal for new physics is lost if a relatively large y, of the order of a percent, is observed [40, 41].

For a given final state f, CP violating contributions can be summarized in the parameter

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A}_f}{A_f}\right|, \tag{11}$$

where A_f and $\overline{A}_f$ are the amplitudes for $D^0 \to f$ and $\overline{D}^0 \to f$ transitions respectively and δ is the strong phase difference between A_f and $\overline{A}_f$. Here ϕ represents the convention-independent weak phase difference between the ratio of decay amplitudes and the mixing matrix.

Presently, experimental information about the $D^0 - \overline{D}^0$ mixing parameters x and y comes from the time-dependent analyses that can roughly be divided into two categories. First, more traditional studies look at the time dependence of $D \to f$ decays, where f is the final state that can be used to tag the flavor of the decayed meson. The most popular is the non-leptonic doubly Cabibbo suppressed decay $D^0 \to K^+\pi^-$. Time-dependent studies allow one to separate the DCSD from the mixing contribution $D^0 \to \overline{D}^0 \to K^+\pi^-$,

$$\Gamma[D^0 \to K^+\pi^-] = e^{-\Gamma t}|A_{K^-\pi^+}|^2 \left[R + \sqrt{R}R_m(y'\cos\phi - x'\sin\phi)\Gamma t + \frac{R_m^2}{4}(y^2+x^2)(\Gamma t)^2\right], \tag{12}$$

where R is the ratio of DCS and Cabibbo favored (CF) decay rates. Since x and y are small, the best constraint comes from the linear terms in t that are also *linear* in x and y. A direct extraction of x and y from Eq. (12) is not possible due to unknown relative strong phase δ_D of DCS and CF amplitudes [44], as $x' = x\cos\delta_D + y\sin\delta_D$, $y' = y\cos\delta_D - x\sin\delta_D$. This phase can be measured independently. The corresponding formula can also be written [40] for $\overline{D}^0$ decay with $x' \to -x'$ and $R_m \to R_m^{-1}$.

Second, D^0 mixing can be measured by comparing the lifetimes extracted from the analysis of D decays into the CP-even and CP-odd final states. This study is also sensitive to a *linear* function of y via

$$\frac{\tau(D \to K^-\pi^+)}{\tau(D \to K^+K^-)} - 1 = y\cos\phi - x\sin\phi\left[\frac{R_m^2 - 1}{2}\right]. \tag{13}$$

Time-integrated studies of the semileptonic transitions are sensitive to the *quadratic* form x^2+y^2 and at the moment are not competitive with the analyses discussed above.

The construction of new tau-charm factories CLEO-c and BES-III will introduce new *time-independent* methods that are sensitive to a linear function of y. One can again use the fact that heavy meson pairs produced in the decays of heavy quarkonium resonances have the useful property that the two mesons are in the CP-correlated states [45].

By tagging one of the mesons as a CP eigenstate, a lifetime difference may be determined by measuring the leptonic branching ratio of the other meson. Its semileptonic *width* should be independent of the CP quantum number since it is flavor specific, yet its *branching ratio* will be inversely proportional to the total width of that meson. Since we know whether this $D(k_2)$ state is tagged as a (CP-eigenstate) $D_\pm$ from the decay of $D(k_1)$ to a final state S_σ of definite CP-parity $\sigma = \pm$, we can easily determine y in terms of the semileptonic branching ratios of $D_\pm$. This can be expressed simply by introducing the ratio

$$R_\sigma^L = \frac{\Gamma[\psi_L \to (H \to S_\sigma)(H \to Xl^\pm\nu)]}{\Gamma[\psi_L \to (H \to S_\sigma)(H \to X)]\ Br(H^0 \to Xl\nu)}, \tag{14}$$

where X in $H \to X$ stands for an inclusive set of all final states. A deviation from $R_\sigma^L = 1$ implies a lifetime difference. Keeping only the leading (linear) contributions due to mixing, y can be extracted from this experimentally obtained quantity,

$$y \cos \phi = (-1)^L \sigma \frac{R_\sigma^L - 1}{R_\sigma^L}. \tag{15}$$

The current experimental upper bounds on x and y are on the order of a few times 10^{-2}, and are expected to improve significantly in the coming years. To regard a future discovery of nonzero x or y as a signal for new physics, we would need high confidence that the Standard Model predictions lie well below the present limits. As was recently shown [41], in the Standard Model, x and y are generated only at second order in $SU(3)_F$ breaking,

$$x\,,\, y \sim \sin^2 \theta_C \times [SU(3) \text{ breaking}]^2 \,, \tag{16}$$

where θ_C is the Cabibbo angle. Therefore, predicting the Standard Model values of x and y depends crucially on estimating the size of $SU(3)_F$ breaking. Although y is expected to be determined by the Standard Model processes, its value nevertheless affects significantly the sensitivity to new physics of experimental analyses of D mixing [40].

Theoretical predictions of x and y span several orders of magnitude. The predictions obtained in the framework of the Standard Model are not exception, as evidenced from Fig. 1[3]. Roughly, there are two approaches, neither of which give very reliable results because m_c is in some sense intermediate between heavy and light. The "inclusive" approach is based on the operator product expansion (OPE). In the $m_c \gg \Lambda$ limit, where Λ is a scale characteristic of the strong interactions, ΔM and $\Delta \Gamma$ can be expanded in terms of matrix elements of local operators [48]. Such calculations yield $x, y < 10^{-3}$. The use of the OPE relies on local quark-hadron duality, and on Λ/m_c being small enough to allow a truncation of the series after the first few terms. The charm mass may not be large enough for these to be good approximations, especially for nonleptonic D decays. An observation of y of order 10^{-2} could be ascribed to a breakdown of the OPE or of duality, but such a large value of y is certainly not a generic prediction of OPE analyses. The "exclusive" approach sums over intermediate hadronic states, which may be modeled or fit to experimental data [49]. Since there are cancellations between states within a given $SU(3)$ multiplet, one needs to know the contribution of each state with high precision. However, the D is not light enough that its decays are dominated by a few final states. In the absence of sufficiently precise data on many decay rates and on strong phases, one is forced to use some assumptions. While most studies find $x, y < 10^{-3}$, Refs. [49] obtain x and y at the 10^{-2} level by arguing that $SU(3)_F$ violation is of order unity, but the source of the large $SU(3)_F$ breaking is not made explicit. It was also shown that phase space effects alone provide enough $SU(3)_F$ violation to induce $y \sim 10^{-2}$ [41]. Large effects in y appear for decays close to D threshold, where an analytic expansion in $SU(3)_F$ violation is no longer possible. Thus, theoretical calculations of x and y are quite uncertain, and the values near the

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[3]Compilation of the $D^0 - \overline{D}^0$ mixng predictions is known as the Nelson plot [46]. In order to obtain a compilation of the Standard Model (Fig. 1) and new physics (Fig. 2) predictions for charm mixing, we updated and corrected Ref. [46] to remove double counting of predictions. We also separated the Standard Model and new physics predictions into two separate plots [47].

current experimental bounds cannot be ruled out. Therefore, it will be difficult to find a clear indication of physics beyond the Standard Model in $D^0 - \overline{D}^0$ mixing measurements alone. The only robust potential signal of new physics in charm system at this stage is CP violation.
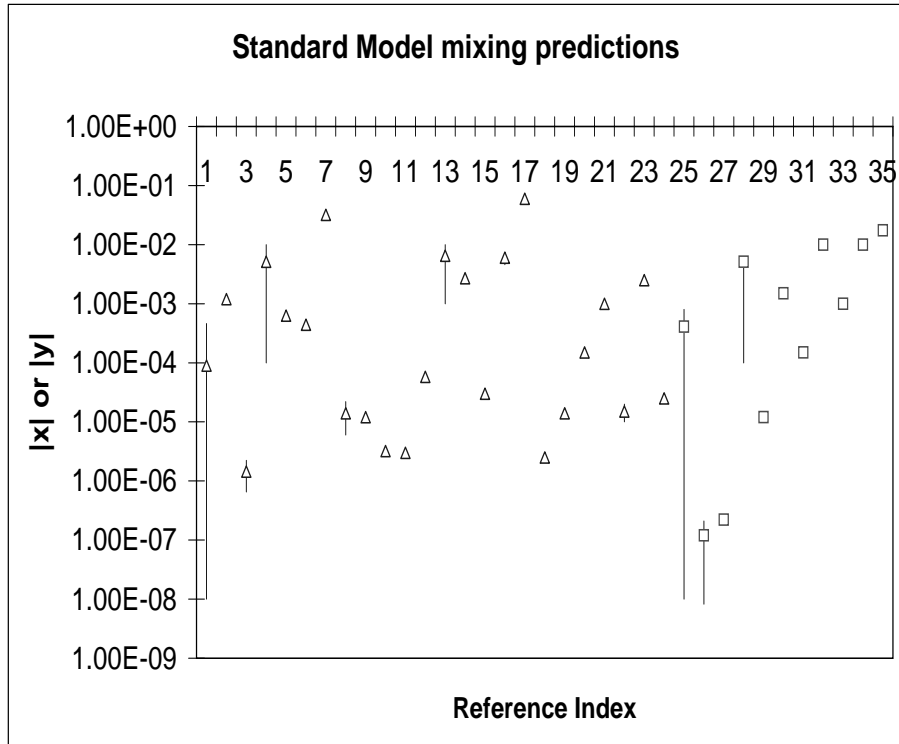
Acknowledgments

Figure 1: Standard Model predictions for $|x|$ (open triangles) and $|y|$ (open squares). Horizontal line references are tabulated in Table 4.

References

[1] A. A. Petrov, eConf **C0304052**, WG506 (2003) [arXiv:hep-ph/0307322].

[2] R. Chistov, "Charm Spectroscopy", *these proceedings.*

[3] W. Johns, "Semileptonic and rare charm decays", *these proceedings.*

[4] G. Boca, "D mixing and lifetimes", *these proceedings.*

Mass difference x	Refrence Index	Citation
$(0.9 \pm 3.7) \times 10^{-4}$	1	Phys. Rev. D 26, 143 (1982)
1.2×10^{-3}	2	Phys. Lett. B128, 240 (1983)
$(1.44 \pm 0.79) \times 10^{-6}$	3	Z. Phys. C 27, 515 (1985)
$(0.01 - 10) \times 10^{-2}$	4	Phys. Lett. B 164, 170 (1985)
6.3×10^{-4}	5	Phys. Rev. D 33, 179 (1986)
4.4×10^{-4}	6	Phys. Rev. D 35, 3484 (1987)
3.2×10^{-2}	7	Phys. Lett. B224, 71 (1990)
$(1.4 \pm 0.8) \times 10^{-5}$	8	Nucl. Phys. B403, 71 (1993)
1.2×10^{-5}	9	hep-ph/9407378
3.2×10^{-6}	10	Chin. J. Phys. 32, 1163 (1994)
3.0×10^{-6}	11	hep-ph/9409379
5.8×10^{-5}	12	hep-ph/9508349
$(1 - 10) \times 10^{-3}$	13	hep-ph/9508349
2.7×10^{-4}	14	hep-ph/9508349
3×10^{-5}	15	Phys. Lett. B357, 151 (1995)
$(6.0 \pm 1.4) \times 10^{-3}$	16	Phys. Lett. B357, 151 (1995)
6×10^{-2}	17	Phys. Lett. B357, 151 (1995)
2.5×10^{-6}	18	Phys. Rev. D 56, 1685 (1997)
1.4×10^{-5}	19	Phys. Lett. B 422, 265 (1998)
1.5×10^{-4}	20	Phys. Lett. B 427, 172 (1998)
1.0×10^{-3}	21	Nucl.Phys. B592, 92 (2001)
$(1.5 \pm 0.5) \times 10^{-5}$	22	Phys. Lett. B297, 353 (1992)
2.50×10^{-3}	23	Phys. Rev. D 43, 1641 (1991)
2.50×10^{-5}	24	hep-ph/9706548
Lifetime difference y	Refrence Index	Citation
$-(0.06 - 8.0) \times 10^{-4}$	25	Phys. Rev. D 26, 143 (1982)
$(0.082 - 2.1) \times 10^{-7}$	26	Phys. Lett. B 128, 240 (1983)
2.2×10^{-7}	27	Z. Phys. C 27, 515 (1985)
$(0.01 - 10) \times 10^{-2}$	28	Phys. Lett. B 164, 170 (1985)
1.2×10^{-5}	29	hep-ph/9407378
1.5×10^{-3}	30	Phys. Lett. B 379, 249 (1996)
1.0×10^{-4}	31	Phys. Lett. B 427, 172 (1998)
1.0×10^{-2}	32	Phys. Rev. Lett. 83, 4005 (1999)
1.0×10^{-3}	33	Nucl.Phys. B592, 92 (2001)
1.0×10^{-2}	34	Phys. Rev. D65, 054034 (2002)
$(1.5 - 2.0) \times 10^{-2}$	35	Phys. Rev. D 43, 1641 (1991)

Table 4: Theoretical predictions for mixing parameters (Standard Model). The notation "$\pm$" indicates the range of predictions.

Mass difference x	Refrence Index	Citation
6.0×10^{-2}	1	Yad. Phys. 34, 435 (1981)
$(0.11 \pm 1.8) \times 10^{-3}$	2	Phys. Rev. D 26, 143 (1982)
5×10^{-2}	3	Phys. Lett. B154, 287 (1985)
$(0.6 - 6.0) \times 10^{-5}$	4	Phys. Lett. B154, 287 (1985)
$(0.6 - 6.0) \times 10^{-4}$	5	Phys. Lett. B154, 287 (1985)
$(5.05 \pm 1.85) \times 10^{-2}$	6	Phys. Lett. B154, 287 (1985)
$(0.06 - 60) \times 10^{-8}$	7	Phys. Lett. B154, 287 (1985)
$(0.06 - 60) \times 10^{-5}$	8	Phys. Lett. B154, 287 (1985)
6.3×10^{-6}	9	Z. Phys. C 30, 293 (1986)
8.5×10^{-3}	10	Z. Phys. C 30, 293 (1986)
$(0.15 - 90) \times 10^{-3}$	11	Phys. Lett. B190, 93 (1987)
4.4×10^{-2}	12	Phys. Rev. D 35, 3484 (1987)
$(0.1 - 10) \times 10^{-2}$	13	Phys. Lett. B205, 540 (1988)
$(0.06 - 40) \times 10^{-4}$	14	Phys. Rev. D 39, 878 (1989)
0.1	15	Phys. Lett. B309, 337 (1993)
0.11	16	Phys. Rev. D 48, 979 (1993)
$(0.006 - 120) \times 10^{-3}$	17	hep-ph/9409379
$(0.004 - 120) \times 10^{-3}$	18	hep-ph/9409379
$(0.06 - 120) \times 10^{-3}$	19	hep-ph/9409379
6.3×10^{-4}	20	hep-ph/9409379
5×10^{-2}	21	hep-ph/9508349
$(0.6 - 6) \times 10^{-5}$	22	Phys. Rev. D 55, 3156 (1997)
$(0.6 - 6) \times 10^{-1}$	23	Phys. Rev. D 55, 3156 (1997)
$(0.6 - 6) \times 10^{-6}$	24	Phys. Rev. D 55, 3156 (1997)
5×10^{-4}	25	Phys. Rev. Lett. 78, 2300 (1997)
6×10^{-4}	26	hep-ph/9704316
$(0.06 - 600) \times 10^{-4}$	27	Phys. Lett. B416, 184 (1998)
3×10^{-3}	28	Phys. Rev. D 60, 013005 (1999)
2.1×10^{-2}	29	Phys. Rev. D 61, 075011 (2000)
3.0×10^{-2}	30	Phys. Rev. D 62, 033002 (2000)
$0.001 - 0.05$	31	hep-ph/0110106

Table 5: Theoretical predictions for mixing parameters (New Physics). The notation "$\pm$" indicates the range of predictions based on the model parameter space bounded by the data available *at the time of publication*.
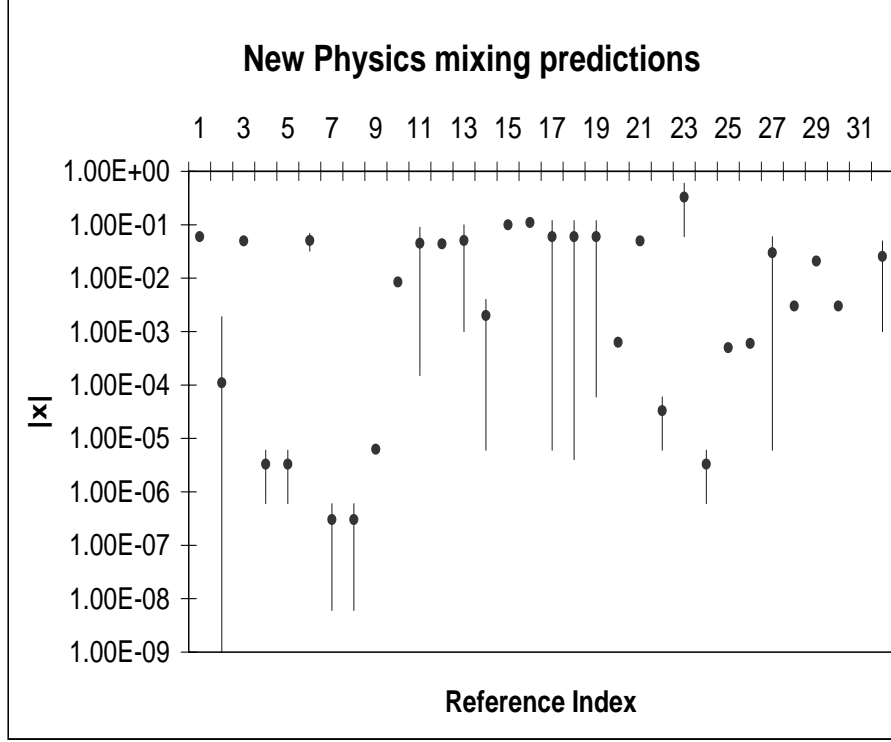
Figure 2: New Physics predictions for $|x|$. Horizontal line references are tabulated in Table 5.

[5] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **90**, 242001 (2003).

[6] D. Besson *et al.* (CLEO Collaboration), hep-ex/0305100, submitted to Phys. Rev. D.

[7] K. Abe *et al.* (Belle Collaboration), BELLE-CONF-0340, BELLE-CONF-0334, contributed to the EPS and LP03 conferences, http://belle.kek.jp/conferences/LP03-EPS.

[8] D.E. Groom *et al.* (Particle Data Group), Eur. Phys. J. C **15**, 1 (2000).

[9] S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985).

[10] M. Di Pierro and E. Eichten, Phys. Rev. D **64**, 114004 (2001).

[11] S. N. Gupta and J. M. Johnson, Phys. Rev. D **51**, 168 (1995).

[12] J. Zeng, J. W. Van Orden and W. Roberts, Phys. Rev. D **52**, 5229 (1995).

[13] Y. S. Kalashnikova, A. V. Nefediev and Y. A. Simonov, Phys. Rev. D **64**, 014037 (2001).

[14] D. Ebert, V. O. Galkin and R. N. Faustov, Phys. Rev. D **57**, 5663 (1998) [Erratum-ibid. D **59**, 019902 (1999)].

[15] R. Lewis and R. M. Woloshyn, Phys. Rev. D **62**, 114507 (2000); J. Hein *et al.*, Phys. Rev. D **62**, 074503 (2000); G. S. Bali, Phys. Rev. D **68**, 071501 (2003) [arXiv:hep-ph/0305209].

[16] A. Dougall, R. D. Kenway, C. M. Maynard and C. McNeile, Phys. Lett. B **569**, 41 (2003) [arXiv:hep-lat/0307001].

[17] W. A. Bardeen and C. T. Hill, Phys. Rev. D **49**, 409 (1994); W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D **68**, 054024 (2003) [arXiv:hep-ph/0305049]; D. Ebert, T. Feldmann and H. Reinhardt, Phys. Lett. B **388**, 154 (1996); D. Ebert, T. Feldmann, R. Friedrich and H. Reinhardt, Nucl. Phys. B **434**, 619 (1995); M. A. Nowak, M. Rho and I. Zahed, Phys. Rev. D **48**, 4370 (1993); M. A. Nowak, M. Rho and I. Zahed, arXiv:hep-ph/0307102; A. Deandrea, G. Nardulli and A. D. Polosa, Phys. Rev. D **68**, 097501 (2003) [arXiv:hep-ph/0307069].

[18] T. Barnes, F. E. Close and H. J. Lipkin, Phys. Rev. D **68**, 054006 (2003) [arXiv:hep-ph/0305025].

[19] H. Y. Cheng and W.-S. Hou, Phys. Lett. B **566**, 193 (2003) [arXiv:hep-ph/0305038].

[20] A. P. Szczepaniak, Phys. Lett. B **567**, 23 (2003) [arXiv:hep-ph/0305060].

[21] R. N. Cahn and J. D. Jackson, Phys. Rev. D **68**, 037502 (2003) [arXiv:hep-ph/0305012]; Y. B. Dai, C. S. Huang, C. Liu and S. L. Zhu, arXiv:hep-ph/0306274.

[22] K. Abe *et al.* (Belle Collaboration), hep-ex/0307021, submitted to Phys. Rev. D.

[23] E. van Beveren et al., Z. Phys. C 30, 615 (1986); E. van Beveren and G. Rupp, hep-ph/0304105; E. van Beveren and G. Rupp, Phys. Rev. Lett. 91, 012003 (2003); J. Weinstein and N. Isgur, Phys. Rev. D 41, 2236 (1990).

[24] H.J. Lipkin, Phys. Lett. B. 70, 113 (1977).

[25] M. Suzuki and S.F. Tuan, Phys. Lett. B. 133, 125 (1983).

[26] S. Godfrey, Phys. Lett. B **568**, 254 (2003) [arXiv:hep-ph/0305122]; P. Colangelo and F. De Fazio, Phys. Lett. B **570**, 180 (2003) [arXiv:hep-ph/0305140].

[27] T. E. Browder, S. Pakvasa and A. A. Petrov, arXiv:hep-ph/0307054, Phys. Lett. B, in press.

[28] W. Lucha and F. F. Schoberl, arXiv:hep-ph/0309341.

[29] A. Datta and P. J. O'donnell, Phys. Lett. B **572**, 164 (2003) [arXiv:hep-ph/0307106].

[30] S. Veseli and I. Dunietz, Phys. Rev. D **54**, 6803 (1996).

[31] G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996); A. J. Buras, M. Jamin and P. H. Weisz, Nucl. Phys. B **347**, 491 (1990); M. Ciuchini, E. Franco, G. Martinelli, L. Reina and L. Silvestrini, Z. Phys. C **68**, 239 (1995).

[32] M. Battaglia *et al.*, arXiv:hep-ph/0304132.

[33] S. Aoki *et al.* [JLQCD Collaboration], arXiv:hep-ph/0307039.

[34] J. G. Korner, A. I. Onishchenko, A. A. Petrov and A. A. Pivovarov, Phys. Rev. Lett. **91**, 192002 (2003) [arXiv:hep-ph/0306032].

[35] B. Grinstein, Phys. Rev. Lett. **71**, 3067 (1993).

[36] Z. Ligeti, I. W. Stewart and M. B. Wise, Phys. Lett. B **420**, 359 (1998).

[37] D. Pedrini [the FOCUS Collaboration], arXiv:hep-ph/0307137; M. B. Voloshin, Phys. Rept. **320**, 275 (1999); B. Guberina, B. Melic and H. Stefancic, Phys. Lett. B **484**, 43 (2000).

[38] A. Juttner and J. Rolf, arXiv:hep-ph/0306299;

[39] A. Datta, D. Kumbhakar, Z. Phys. C**27**, 515 (1985); A. A. Petrov, Phys. Rev. D**56**, 1685 (1997); E. Golowich and A. A. Petrov, Phys. Lett. B **427**, 172 (1998).

[40] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, A. Petrov, Phys. Lett. B **486**, 418 (2000).

[41] A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002).

[42] S. Fajfer, arXiv:hep-ph/0306263.

[43] S. Fajfer, S. Prelovsek, P. Singer and D. Wyler, Phys. Lett. B **487**, 81 (2000).

[44] A. F. Falk, Y. Nir and A. A. Petrov, JHEP **9912**, 019 (1999).

[45] D. Atwood and A. A. Petrov, arXiv:hep-ph/0207165.

[46] H. N. Nelson, in *Proc. of the 19th Intl. Symp. on Photon and Lepton Interactions at High Energy LP99* ed. J.A. Jaros and M.E. Peskin, arXiv:hep-ex/9908021.

[47] For the most updated version, see http://www.physics.wayne.edu~apetrov/mixing/.

[48] H. Georgi, Phys. Lett. B297, 353 (1992); T. Ohl, G. Ricciardi and E. Simmons, Nucl. Phys. B403, 605 (1993); I. Bigi and N. Uraltsev, Nucl. Phys. B **592**, 92 (2001).

[49] J. Donoghue, E. Golowich, B. Holstein and J. Trampetic, Phys. Rev. D33, 179 (1986); L. Wolfenstein, Phys. Lett. B164, 170 (1985); P. Colangelo, G. Nardulli and N. Paver, Phys. Lett. B242, 71 (1990); T.A. Kaeding, Phys. Lett. B357, 151 (1995). A. A. Anselm and Y. I. Azimov, Phys. Lett. B **85**, 72 (1979);

[50] I. I. Bigi and A. I. Sanda, *CP violation* (Cambridge University Press, 2000).

[51] D. Pedrini, J. Phys. G **27**, 1259 (2001).

[52] I. I. Bigi and A. I. Sanda, Phys. Lett. B **171**, 320 (1986).

[53] A. A. Petrov, Proc. of the *5th Workshop on Continuous Advances in QCD*, pp. 102-114; arXiv:hep-ph/0209049.